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# Multi stress testing of OPV modules for accurate predictive ageing and reliability predictions

V. Stoichkov, D. Kumar, P. Tyagi, J. Kettle\*

**Abstract**—OPV degradation remains a complex challenge and previous studies have been shown the degradation to be a function of multiple stresses, so it can be inaccurate to predict failure rates using single stress tests. In this paper, a new testing methodology whereby multiple stresses are applied simultaneously using a ‘design of experiment (DOE) approach’ is reported and used for predictive ageing of modules. A multi-stress data is used for predictive ageing of OPV modules under different stress levels; a General-Log-Linear (GLL) life model has been adapted and applied in order to predict the life of OPV modules and this is compared to experimental data, which shows that a close estimation of simulated lifetime is obtained (within 18% accuracy). The life test models can be used for predicting ageing of OPV modules in different geographic locations and could be used to account for different degradation rates due to seasonal climatic variations. Furthermore, by using the DOE data, we show how the major stress factors can be screened and their statistical significance upon degradation quantified using ANOVA. One of the potential benefits of using this approach for OPV degradation studies is that additional factors could be added to study the impact on degradation to provide a more comprehensive study.

**Index Terms**—photovoltaics, Organic PVs, reliability

## I. INTRODUCTION

**S**TABILITY remains a critical issue for researchers and industrialists in Organic Photovoltaic (OPV) research and Accelerated Life Testing (ALT) is regularly used, for example, to identify optimal material sets, provide relative comparisons of module stability, improve encapsulation or provide information of failure mechanisms [1-4]. For almost all previous studies, one or (maximum) two degradation/stress factors has been applied to OPV modules to evaluate their stability. This could be detrimental to the conclusions of the experiment as light induced, thermal and humidity induced defects are not independent of one another and should be considered simultaneously [4]. Furthermore, whilst in an indoor environment, OPVs are usually operated under controlled conditions, in the outdoors, the OPV usually

experience multiple stresses that continuously vary with time including light, temperature and humidity [5-6].

Design of Experiments (DOE) is a much more efficient strategy than one or two factors at a time experiments and allows for the investigation of how a factor affects the stability in the presence of other factors (known as an ‘interaction’) [7]. We define ‘interaction’ as the relationship whereby the effect that a stress factor (e.g. light, temperature, humidity) has on the OPV module is altered due to the presence of one or more other stress factors. This is particularly significant in OPVs as very often interactions increase the degradation significantly; for example, when temperature and humidity are simultaneously applied, much greater degradation is observed as compared to a scenario whereby temperature or humidity is increased on its own [8]. Hence, to fully characterize OPV degradation, investigation of the individual stress factors and their interactions should be undertaken. This will ensure the full range of weaknesses in OPV are resolved and provide an accelerated test that is more realistic to the outdoor conditions. Further benefits of multistress testing is that higher Acceleration Factors (AF) are possible, which will increase the speed of testing leading to faster acquisition of lifetime data [4].

In this paper, multistress testing is applied in order to improve predictive ageing of OPV modules. To achieve this, a Generalised Log-Linear (GLL) life-stress relationship has been deployed to predict the life of OPVs in an outdoor environment. Using the accelerated testing results obtained, the relationship between stresses and OPV life is established, and a life distribution model can be constructed. Subsequently, an improved method whereby estimated life of an OPV modules in an outdoor field is presented. There are additional benefits to using this approach; a statistical technique ‘analysis of variance’ (‘ANOVA’) has been applied to the data so that the individual effect of each stress and their interactions can be quantified and their impact compared between one another.

## II. EXPERIMENTAL

### A. Experimental procedure

All testing was undertaken using the ‘InfinityPV’ mini-module [9]. The structure is discussed in other papers [1,4]

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and the structure active consists of mixed bulk heterojunction with Poly(3-hexylthiophene-2,5-diyl) (P3HT) and [6,6]-phenyl-C<sub>61</sub>-butyric acid methyl ester (PC<sub>61</sub>BM). The module consists of eight individual cells which are monolithically connected so that there is only a single anode and cathode for connection to external circuitry. For this work, three stress factors were identified (light, temperature and relative humidity). A Weiss UK testing chamber was used for thermal humidity with a transparent window. Through the window, a halogen light soaker was mounted to enable simultaneous light soaking (GB Sol Ltd, Taffs Well, Wales, UK). Each test used a different temperature, irradiance and relative humidity (RH) level. For each test, three OPV mini-modules were used and all data acquisition was acquired in-situ. Current-Voltage (I-V) measurements were made every 30 minutes calculating the Power Conversion Efficiency (PCE) which is used to monitor the decay of the module. PCE was only calculated using IV measurements. To fit life test models to ISOS standard testing data, either in-situ degradation data or 'time to failure' needs to be defined. For this paper, we study degradation to 80% or 50% of the original maximum efficiency value (i.e. T80% or T50%). This work focused on testing OPV modules rather than single cells of devices. Previous work has indicated that using single cells for ALT provides inaccurate date fitting [4]. The primary reason for this was that at high stress levels of relative humidity, temperature and light, the OPVs cells degraded rapidly due to overstressing. This increased the number of random failures and led to poor ageing results.

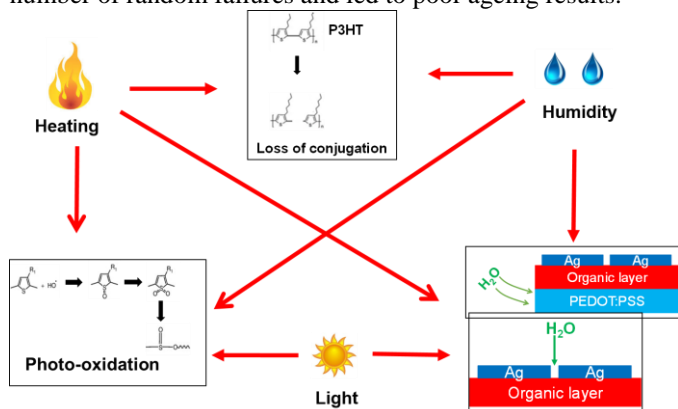


Fig. 1. Degradation processes in the OPV module due to (a) temperature, (b) irradiance and (c) humidity and showing how the stress factors interact with one another.

For data analysis, each module tested was analysed for its T80% and T50% time. Data was uploaded to an internal database with time stamping, module ID and test conditions and time to failure was characterised. Data was analysed using a number of commercial reliability and statistical software packages (Minitab, Reliasoft).

For life model fitting, the 'operational stress' needs to be defined, which are the median weather conditions which was experienced by the outdoor module. This was calculated using weather station data from a Davis Inc. 'Vantage pro' weather station and calibrated silicon reference cell from IMT-solar GmbH located on the roof of the School of Electronic

Engineering, Bangor University, Wales, UK (latitude and longitude of 53.2280N, 4.1280W, respectively), previously reported [6,10]. Data analysis over the period of experiments showed the irradiance level to be 0.18 Sun relative humidity to be 76% and temperature to be 289K.

### B. Test planning using DOE

In factorial designs, multiple factors are investigated simultaneously during the test. There are several techniques for undertaking DOE analysis; however, this work uses a 'two level full factorial design'. Therefore, only two stress levels were applied for all stress factors. By restricting the levels to two and running a full factorial experiment, an investigation of the impact of all stress factors and all their interactions is possible. For this work, three factors; temperature (**A**), relative humidity (**B**) and irradiance (**C**) were considered and therefore requires 8 ( $2^3 = 8$ ) runs. Given the relatively manageable number of experiments, there is no need to reduce the number of experiments using statistical techniques such as confounding; however, for future experiments, this could be applied to keep the number of test runs low should other factors needed to be considered e.g. thermal cycling, vibration, and voltage. For the ( $2^3$ ) design, we were able to test three main effects (**A**), (**B**) and (**C**); three two factor interaction effects (**A · B**, **A · C**, **B · C**), and one three factor interaction effect, (**A · B · C**). The eight treatment combinations corresponding to these runs are (**A**), (**B**), (**C**), (**A · B**), (**A · C**), (**B · C**), (**A · B · C**). The design matrix for the ( $2^3$ ) design is shown in table 1.

The design matrix can be constructed by following the standard order for the treatment combinations to obtain the columns for the main effects and then multiplying the main effects columns to obtain the interaction columns. The treatment combinations are written in such an order that factors are introduced one by one with each new factor being combined with the preceding terms and these are highlighted in the columns. Whilst the table is shown in the standard ('Yates') order, for this work, a random order was used in the experiment (column run order is given in Table 1) to minimise possible exterior effects such as experimental error or module-to-module degradation in between experiments.

Table 1 shows the detailed range of stress conditions and an estimated 'Acceleration factor' for each test based upon data from an earlier test [4]. This allows an estimate of test time to be measured. Ideally, a low test time should be used to obtain data rapidly, however, a trade-off exists as overstressing the modules might lead to erogenous data.

### C. Reliability data analysis

In addition to the DOE analysis, the multistress test data can also be used for predictive ageing. Previous life-model fitting in OPVs have only used a maximum of two stress factors [2,4], so a new strategy must be adopted. Therefore, in this work, the development of bespoke life test model is required. For this reason, the Generalised Log-Linear (GLL) model has

been employed which has previously been used for predictive lifetimes of optical components in an outdoor test condition, where a number of environmental factors impact upon stability [33,34]. The formulation of the GLL model begins with the assumption of a log-linear relation for the characteristic life as shown in eq 1, where  $\alpha_0$  and  $\alpha_z$  are fitting parameter and  $x_z$  is a vector of stresses. For the case of this test,  $z = 3$  as three stress factors are used (temperature, relative humidity and irradiance). The advantage of representing the characteristic life with the GLL relationship is that relationships such as the Arrhenius and inverse power models can be assumed for the stress factors by performing a simple transformation. According to previous studies [2,4], the ‘inverse power’ model can be used for light induced degradation and Arrhenius relationships are suited for temperature and RH stresses.

$$L(t) = \exp[\alpha_0 + \sum_{z=1}^3 \alpha_z x_z] \quad (1)$$

To develop life test models, a 2-point Weibull probability distribution function (PDF) and life model is selected initially. The Weibull PDF is used to model the changes in failure rate,  $f(t)$ , as a function of time. The 2-point Weibull PDF is shown in eq. 2, where  $\beta$  is defined as the shape parameter,  $\eta$  is the scale parameter,  $t$  is the time and  $f(t)$  is the probability of failure.

$$f(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (2)$$

Both the PDF fitting parameters and life model fitting parameters were optimised iteratively using maximum likelihood estimation (MLE). Based upon the parameters extracted from the life model, the simulation of OPV stability can be conducted at the ‘operational’ stress, which is a reduced level to the accelerated conditions, but correlates to the outdoor conditions the OPV is likely to experience. Normal operating conditions was calculated for the period July 2016 for Bangor, Wales, UK.

To compare modelled data to the data obtained in outdoor experiments, a consistent definition of failures was needed. For this work, we have used the life test model to calculate time for 63% of the population of OPV modules tested have declined a particular value [such as 80% of the original value (T80%) or 50% of the original value (T50%)]. The value defined is often referred to as B(63%). By considering eq. 2, when  $t = \eta$ , the cumulative number of failures in the population,  $F(t) = 63\%$ , so  $\eta$  is equivalent to B(63%). To compare the experiment with simulation, outdoor failure times were calculated when approximately 63% of the modules have reached the failure time (e.g. T80% or T50%).

TABLE I

TEST RUN REPLICATES USED FOR MULTI-STRESS TESTING OF OPV MODULES USING A TWO LEVEL, FULL FACTORIAL DESIGN WITH TWO STRESS LEVELS; -1 RE. THREE STRESS FACTORS WERE CHOSEN; TEMPERATURE, RELATIVE HUMIDITY AND IRRADIANCE.

Test ID	Temp. (K)	Rel. Humidity (%)	Light (sun)	AF based on previous calculations	Estimate time to T80%
1	318 (-1)	67 (-1)	0.5 (-1)	2.89	148
2	318 (-1)	67 (-1)	1 (1)	4.63	92
3	318 (-1)	85 (1)	0.5 (-1)	4.64	92
4	318 (-1)	85 (1)	1 (1)	7.43	57
5	338 (1)	67 (-1)	0.5 (-1)	4.78	89
6	338 (1)	67 (-1)	1 (1)	7.66	55
7	338 (1)	85 (1)	0.5 (-1)	7.68	55
8	338 (1)	85 (1)		12.31	34

### III. RESULTS

#### A. Analysis of Variance (ANOVA)

To analyse the data in detail, ANOVA (Analysis Of Variance) method can be used [11]. This technique allows for comparison of how the degradation of the modules changes under different stress levels and allows for identification of the significant and non-significant effects, which could hopefully better inform future ALT experiments in the OPV community. Furthermore, the understanding of the effects of different variables upon one another can be studied.

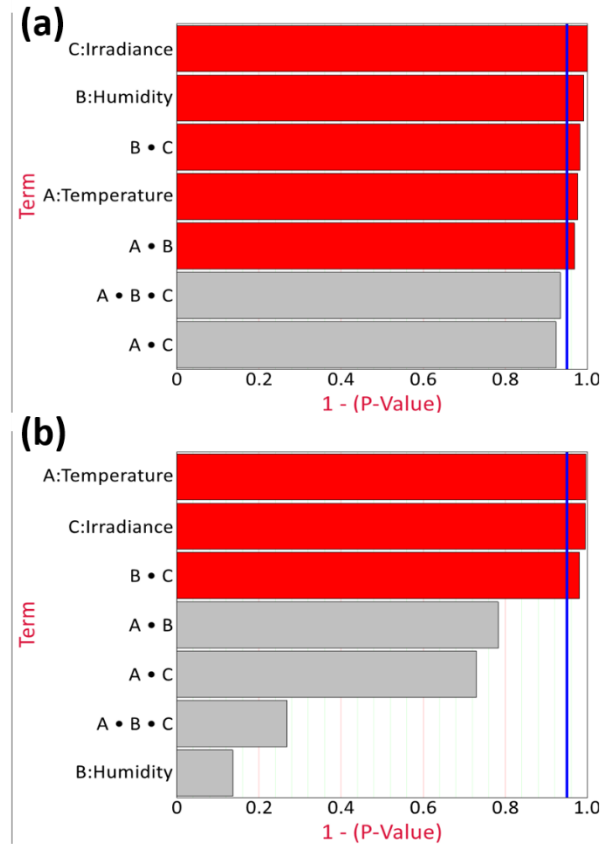


Fig. 2. Pareto chart analysing significant and non-significant factors that affect module degradation to (a) T80% and (b) T50%. The results show the

TABLE II

ANOVA TABLE SHOWING PARTIAL SUM OF SQUARES, F-RATIO AND P-VALUE. ITEMS HIGHLIGHTED IN RED ARE SHOWN TO BE STATISTICALLY SIGNIFICANT AT A RISK LEVEL OF 0.05.

Source of variation	T80% VALUES			T50% VALUES		
	Sum of Squares [Partial]	F Ratio	P Value	Sum of Squares [Partial]	F Ratio	P Value
A:Temp.	8097.1	7.72	0.0004	150450	3.54	0.017
B:Humidity	939.2	6.27	0.0235	51847	8.54	0.010
C:Light	1303.0	8.69	0.0094	14775	2.43	0.138
A • B	2871.9	19.16	0.0005	34013	5.60	0.031
A • C	825.9	5.50	0.0321	9983	1.64	0.218
B • C	537.2	3.58	0.0765	61.8	0.01	0.920
A • B • C	1037.4	6.92	0.0181	37091	6.10	0.025
Residual	582.4	3.88	0.0662	2677	0.44	0.516
Model	2398.3	7.71	0.0004	97130	3.54	0.017

individual and combination of the most significant factors affecting the degradation of the OPV modules

As OPVs have been shown to exhibit large module to module variation even at the same stress testing conditions, it is vital to consider this variation compared to the variation which is inflicted by increasing one or more stress levels. ANOVA method allows for this by calculating the variation in the degradation observed between modules stressed at the same level ('within run variation') and variation caused by changing the stress level ('between run variation').

The experimental data from table 1 has been used to examine whether the between run variation is larger than the within-run variation. To do this, the total variation can be defined by calculating the total sum of squares ( $SS_T$ ). The total sum of squares is split into random variance ( $SS_E$ ) or between run variation ( $SS_R$ ), thus can be defined as  $SS_T = SS_R + SS_E$ . By calculating  $SS_E$  and  $SS_R$ , the mean square of regression ( $MS_R$ ) and mean square of error ( $MS_E$ ) can be calculated. The value for  $MS_R$  is used to measure the between-run variance, that is caused by altering each stress factor. Additionally, the value for  $MS_E$  represents the within-run variance caused by module-to-module variation (or 'noise'). If these are calculated for each stress factor, and interaction, then the effect of the significance of that stress factor compared to the effect of variance can be evaluated, which is achieved using ANOVA. To conduct ANOVA, the following ratio ('the F ratio') is used to test the following two hypotheses:

$$F_O = \frac{MS_R}{MS_E} \quad (3)$$

*H0: There is no difference between the variance caused by stress factor (e.g. light, humidity, temperature) and the variance caused by noise.*

*H1: The variance caused by stress factor (e.g. light, humidity, temperature) is larger than the variance caused by*

*noise.*

To calculate the F-ratio, the ( $MS_R$ ) and mean ( $MS_E$ ) are required, which requires the values of  $SS_E$  and  $SS_R$  to be divided by the respective degrees of freedom. For  $MS_R$ , the degrees of freedom are the total number of groups ('test runs') minus one ( $8 - 1 = 7$ ). For  $MS_E$ , the degrees of freedom are the total samples used for these tests minus the groups ( $24 - 8 = 16$ ). Under the null hypothesis, the ratio follows the  $F$  distribution with degrees of freedom of 7 and 16. Finally, the P value is computed from the F-ratio, and this can be used to calculate the difference between the variance caused by the corresponding stress level change and the variance caused by noise.

By applying ANOVA to the data for T80% and T50% degradation times, the ANOVA table 2 is sourced. The  $P$  value for each single stress or interaction is shown by considering the time taken for modules to degrade to 80% and 50%, respectively. For this work, a significance level  $\alpha$  of 0.05 was used to compare with the  $P$  values. A small  $P$ -value (typically  $\leq 0.05$ ) indicates strong evidence against the null hypothesis, thus leads to the rejection of the null hypothesis and a strong indication that the stress effects module degradation.

From table 2, it is possible to see which source has the most severe effect by considering the  $P$  values, where a lower value indicates a strong effect of the stress factor. It is interesting to note that the significant factors vary depending upon how aged the OPV is. For example, when considering the time T80%, the significant factors affecting degradation in order of precedence are ( $A$  – temperature), ( $C$  – irradiance), ( $A \cdot C$  – the interaction of temperature and irradiance), ( $B$  – humidity) and



( $A \cdot B$  –

*the interaction between temperature and humidity*),

at the significance level of 0.05. While the other factors ( $B \cdot C$ ) and ( $A \cdot B \cdot C$ ), are not significant and can be treated as noise. Clearly, almost all stress factors and interactions, except two, are deemed significant, which we believe is related to the ‘burn in’ effect within OPVs. Burn in is a significant issue for stability of OPVs and the main causes of burn in due to temperature, humidity and irradiance are summarized in figure 1 [13,14]. Burn in mainly occurs due to formation of trap states in polymer by photooxidation, photobleaching, loss of conjugation (by heating) and also formation of an oxide layer at interfaces by the reaction of moisture [13,14]. The data in Table 2 indicates that increasing  $A$ ,  $B$ ,  $C$ , ( $A \cdot C$ ) and ( $A \cdot B$ ) are all shown to significantly increase burn in when compared to the within-run variance caused by module-to-module variation (i.e. ‘noise’ in the experiment). It is worth pointing out that the analysis is conducted by considering how increasing each stress factor affects the degradation, when increased over the lowest stress factor values (i.e. test ID 1 in table 1). This stress level has the lowest test settings for irradiance level, RH and temperature, which are 0.5 Sun, 67% and 318K, respectively.

By contrast, when considering the time taken for modules to reach T50%, the significant factors affecting degradation are only threefold;  $A$ ,  $C$ , and the interaction term, ( $B \cdot C$ ), also at the significance level of 0.05. When comparing to the T80% results, it is possible to conclude that the relative effect of each different stress factors (light, temperature, RH and their interactions) changes, as the modules degrade. This could be explained by two reasons. Firstly, it could be that the failure modes that cause degradation to T50% are only accelerated by increasing three factors;  $A$ ,  $C$ , and the interaction term, ( $B \cdot C$ ). This is possibly because increasing the humidity level from 67% RH does not have a significant effect after the burn in process, however together with light ( $B \cdot C$ ), it leads to increased photo-degradation of the polymer layer. It could be due to the encapsulation, the water ingress into the module is limited and this limits the increase in degradation as humidity is increased. However, during the continuous light exposure the reaction of polymer with humidity increases which degrades the polymer film. The process of photo-degradation occurs when oxygen and moisture reacts with the polymer under light and leads to trap formation.

While temperature ( $A$ ) and light ( $C$ ) affect the long term degradation together with the initial burn in (T80%). The effect of temperature, as discussed previously, is to induce a large phase separation between the polymer and fullerene; and loss of polymer conjugation. These process occur even after burn in, however, at a reduced rate. Similarly, the effect of irradiance reduces after burn in; indicating that the rate of increase in trap creation inside the polymer film reduces.

When considering the residual values in Table 2, the value for residual error is higher for T50% than T80%. Residual error is quantified in terms of the residual sum of squares/mean squares. This reflects the variability of the

measurements in each test run. The sum of squares for the pure error is the sum of the squared deviations of the responses from the mean response in each set of replicates. The value for ‘model’ in table 1 shows the mean sum of squares for all stress factors and interactions. By comparing the residual-to-model ratio, the variation between module degradation to T80% and T50% can be studied. For T80%, this ratio is 0.13 but increases to 0.28 for T50%. So, whilst the significant factors that affect T50% are fewer than for T80%, the module-to-module variation is increasing.

The significant effects can be better represented by the use of a Pareto chart as shown in figure 2, which lists in order how each environmental degradation factor and the interactions affects the degradation, over the range selected in table 1. It is important to note that the analysis was conducted over a finite temperature range and should the temperature ranges alter, then the significance of each stress factor might also alter.

It is worth considering the impact of the factor ( $A$  – *temperature*). Previous studies indicate that temperature does not play a significant impact upon OPV module degradation [1,8,32]. However, these tests were undertaken with only temperature, and no other stress factors, applied. It is clear from the data in this experiment that temperature possesses a much more complex interaction with other stress factors. In particular, it appears to increase degradation significantly when applied in the presence of either humidity and light. This provides confirmation that to fully resolve all defects that are likely to occur during normal operation of an OPV, multi-stress testing is imperative and that single-stress testing provides limited evidence.

#### B. Life test model based on the General-log-linear (GLL) model

In the course of this work, a number of relationships were trialled, however the best fitting was obtained from the data in Table 3 by assuming a Weibull distribution (see eq. 1), an Arrhenius life-stress relationship for temperature and RH and an inverse power life-stress relationship for light. The general log-linear equation (in terms of the life as a function of time) can be expressed as in equation 4, where  $V$  is the Temperature (K),  $H$  is the relative humidity and  $I$  is the irradiance level ( $\text{kW/m}^2$ ):

$$L(t) = \exp \left[ \alpha_0 + \frac{\alpha_1}{V} + \frac{\alpha_2}{H} + \alpha_3 \ln(I) \right] \quad (4)$$

Using maximum likelihood estimation, the fitting parameters were sought. In table 3, the coefficients of each variable are listed along with the fitted parameters from the Weibull PDF. As discussed in previous papers the value for  $\eta$  corresponds to the time taken for 63% of the modules to have reached a degradation time (in this case T80% and T50%). This can provide a direct comparison of experimentally obtained data to compare how the fitted model compares to 2 outdoor experimental data.

Based upon the fitting parameters in table 3, a life versus

stress graph can be developed. Shown in figure 3 are the life-stress relationship for (a) temperature, (b) RH and (c) irradiance by considering the time for the modules to degrade to T50%, whilst the other two stress factors are kept constant. All show the expected trends; as the stress level is reduced, the time for the module to degrade has decreased.

TABLE III  
FITTING PARAMETERS FOR THE WEIBULL PROBABILITY DISTRIBUTION FUNCTION  
AND GENERAL LOG-LINEAR RELATIONSHIP FROM EQUATION 2 AND 4,  
RESPECTIVELY.

Test ID	T80%	T50%
$\alpha_0$	-2.36	-1.43
$\alpha_1$	2578.43	2532.87
$\alpha_2$	-0.03	-0.015
$\alpha_3$	-0.89	-0.39
$\eta$	224.71	835.81
$\beta$	1.88	2.80

### C. Acceleration Factor demonstrating the operational versus accelerated stress levels

The acceleration factor (AF) is an important characteristic for lifetime analysis and represents the constant multiplier between the two stress levels. It can be used to estimate the increased degradation as the stress level rises. For the GLL model used in this work, the AF is defined in equation 5. In this case,  $V_O$  and  $V_A$  are the temperatures at operational stress and accelerated stress (in K), respectively.  $H_O$  and  $H_A$  are the RH at 'use' stress and accelerated stress (in % RH), respectively, and  $I_O$  and  $I_A$  are the irradiances at operational stress and accelerated stress (in Sun), respectively.

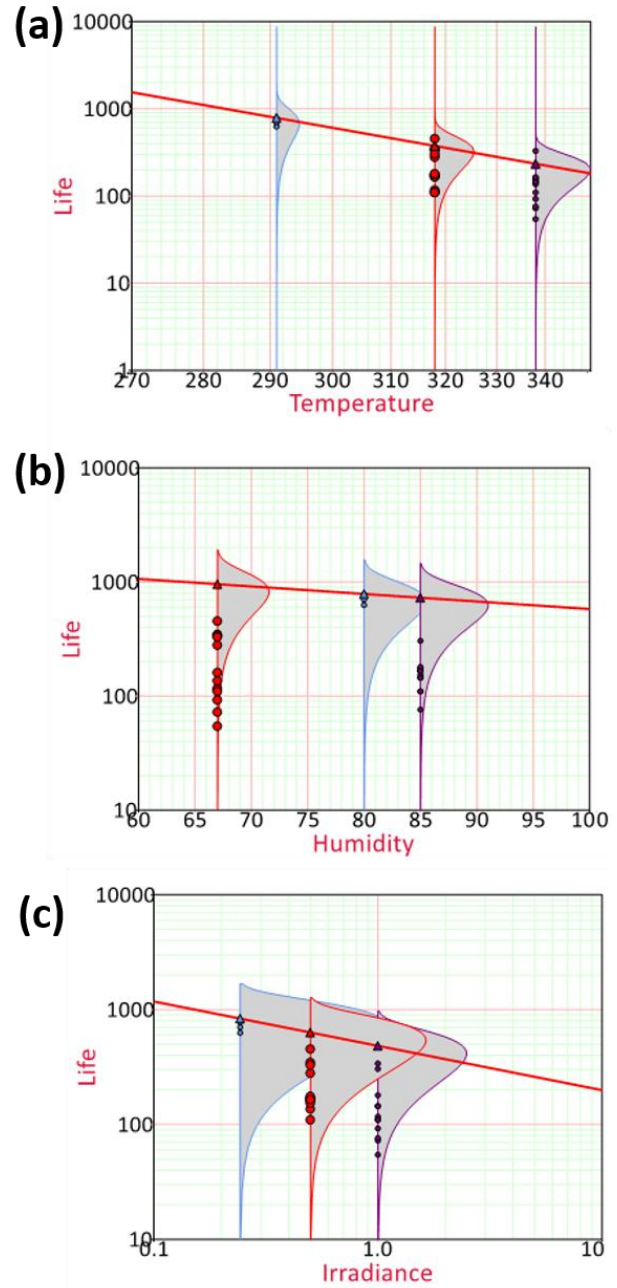


Fig. 3. Mean life (hours) versus stress data showing the experimental data and fitted modules for OPVs to degrade to T50% for life as a function of a) temperature b) relative humidity and c) irradiance. Overlaid on the data is also the outdoor experimental data (blue probability distribution function) to show the good overlap with predictive ageing model.

Figure 4 shows the AF versus temperature, RH and Light individually while the other two stresses are kept constant. The 'use' or operational conditions are for Bangor, Wales, UK, previously reported [6,10] and is discussed in the experimental section of this paper. In the case of T80% and T50%, we see that increasing light, temperature or RH (over the range selected) has a differing impacts upon the degradation. AF considers the impact of environmental conditions on degradation relative to the chosen climate (Bangor, UK). This particular climate has high levels of RH, so the AF due to humidity cannot be increased greatly as the

upper range is narrow. However, if the RH is reduced to 50% (similar to conditions to e.g. Madrid, Spain), then the AF < 0.5, so the degradation would be less than half the value expected for Bangor, assuming the temperature and irradiance levels were the same.

Increasing either the RH or temperature has an exponential effect upon degradation. However, when considering the AF as a function of irradiance level, a sub-linear relationship is evident, consistent with other reports [4]. This result is particularly significant for those undertake high concentrated light experiments, as it is evident for increasing light levels, the degradation has a lesser and lesser impact on light induced degradation.

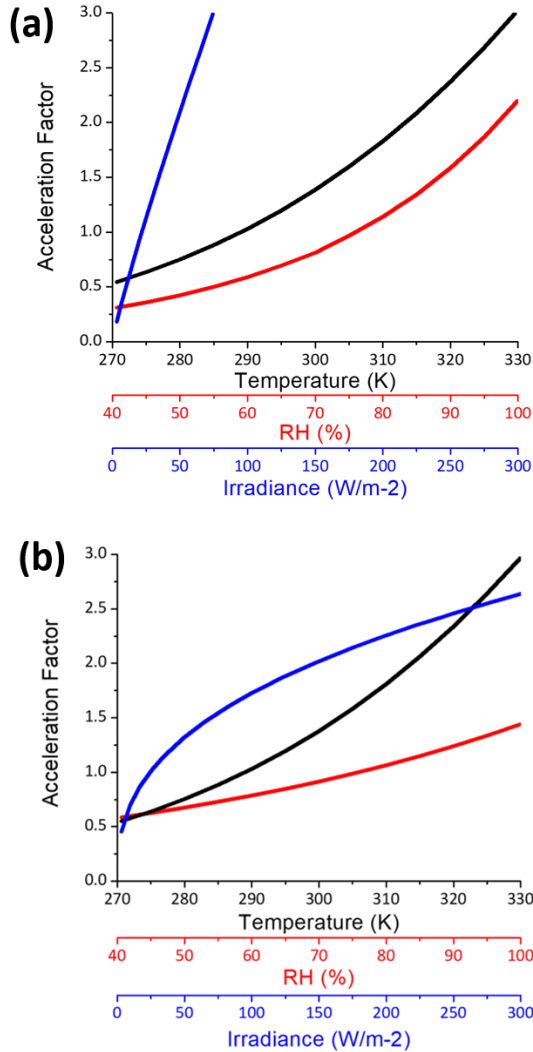


Fig. 4. Acceleration factor (AF) as a function of Temperature, RH and Light for a) T80% and b) T50% mark. The AF is shows the expected increase in degradation in mean life as light, temperature or relative humidity is increased whilst the other factor is kept constant. The AF is calculated relative the degradation expected under normal operational conditions for Bangor, Wales (RH = 76%, Temperature = 289K, Light = 0.18 Sun).

When considering the AF for time taken for the modules to reach T80%, it is worth noting that light has a significantly greater impact. This is consistent with the ANOVA analysis. This is likely due to the burn-in effect in the first 200 hours

because burn in effects are dominated by the light induced trap formation, caused by the rapid polymer photo-oxidation and photo-bleaching and secondly fullerene dimerization during continuous light exposures. In terms of the AF for time taken for the modules to reach T50%, the stress factors have a similar level of impact on degradation.

$$A_F = \frac{L_{USE}}{L_{Accelerated}} = \frac{\exp\left[\alpha_0 + \frac{\alpha_1}{V_U} + \frac{\alpha_2}{H_U} + \alpha_3 \ln(I_U)\right]}{\exp\left[\alpha_0 + \frac{\alpha_1}{V_A} + \frac{\alpha_2}{H_A} + \alpha_3 \ln(I_A)\right]} = \exp\left[\alpha_1\left(\frac{1}{V_U} - \frac{1}{V_A}\right) + \alpha_2\left(\frac{1}{H_U} - \frac{1}{H_A}\right) + \alpha_3 \ln(I_U/I_A)\right] \quad (5)$$

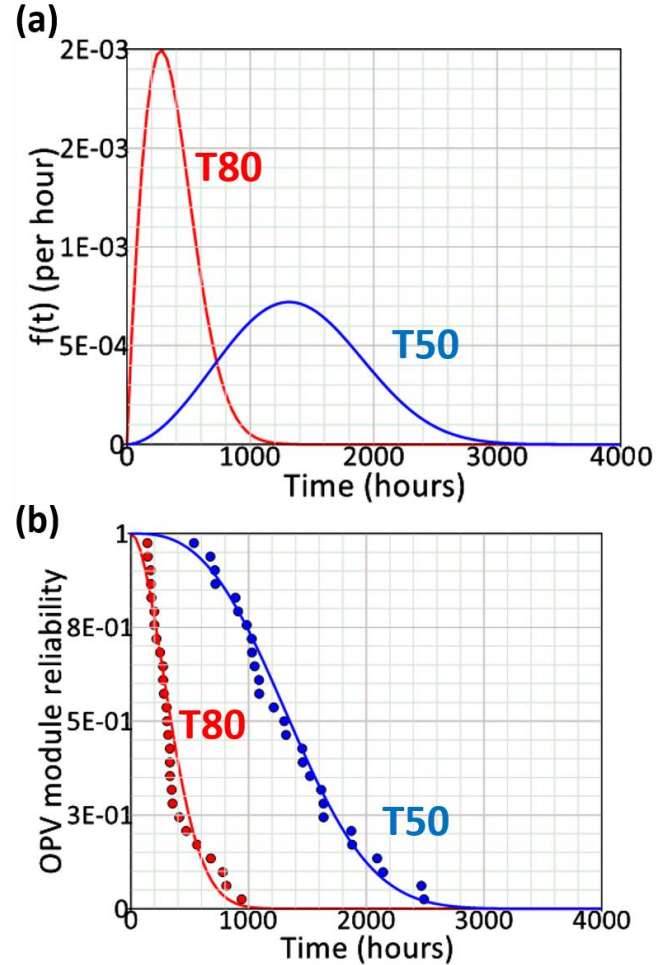


Fig. 5. (a) The failure rate,  $f(t)$ , and (b) the Module reliability,  $R(t)$ , as a function of time as ageing progresses under normal operational conditions for Bangor, Wales (RH = 76%, Temperature = 16°C, Light = 0.18 Sun)

#### D. Probability density function and module reliability

In order to predict the reliability as a function of time at the operational stress, a Weibull probability distribution function was applied to model the changes in failure rate under normal operating conditions. The Weibull PDF is used to model the changes in failure rate,  $f(t)$ , as ageing progresses. Shown in figure 5(a) is how  $f(t)$  changes to reach times of T80 and T50 based upon data supplied from table 3 using the calculated values for  $\beta$  (the shape parameter) and  $\eta$  (the scale parameter).



In both cases  $f(t) = 0$  at  $t = 0$ , which is to be expected, as in both cases  $\beta > 1$  (see table 3). This indicates that the failure rate is increasing with time (as demonstrated in figure 5(a)) and that the ageing process in an OPV is governed by ‘wear out,’ rather than early life failures.

Based upon the  $f(t)$ , as estimate of module reliability  $R(t)$  can be made using the eq. 6.

$$R(t) = 1 - \int_0^t f(t) \cdot dt \quad (6)$$

In Figure 5 (b), the module reliability  $R(t)$  as a function of time is plotted assuming the operational stress levels are applied, which are based on collected weather data for Bangor, Wales, UK i.e. temperature  $T=289K$ ,  $RH=76\%$  and Light dose of 0.18 Sun. Overlaid on the graph for  $R(t)$  as a function of time are all of the data points from the undertaken in table 1, which have been extrapolated to the operation stress levels. It can be seen that reliability decrease as a function of time. It can be expected that all modules would have reached T80% by 1100 hours and T50% by 2900 hours. More specifically, table 4 shows a comparison of simulated life versus data obtained experimentally (described in [4]). It is evident from table 4, that the time taken for 63% of the modules to have reached T80% ( $\eta$ ) is simulated to be 403 hours, as compared to a value of 276 in experiments. However, a closer match is obtained for predicting T50% times, with accuracy of degradation estimated to within 20%. The reason for this is likely to be linked to the burn-in effect in OPVs which makes early life prediction of lifetime difficult.

TABLE IV

SIMULATED (PREDICTED) LIFE FOR THE MODULES TO HAVE REACHED T80 AND T50 COMPARED TO EXPERIMENTAL DATA OBTAINED IN JULY 2016.

	Experimental	Simulated	Experimental	Simulated
	$\eta$ – T80%	$\eta$ – T80%	$\eta$ – T50%	$\eta$ – T50%
Bangor –	276	403	1301	1537
July 2016		(+40%)		(+18%)

#### IV. CONCLUSION

OPV degradation remains a complex challenge for the commercialisation of the technology. New strategies to predict the ageing of modules is required better inform academics and industrialists working in this area. As OPV degradation has been shown to be a function of multiple stresses, it can be inaccurate to predict failure rates using single stresses with high levels of confidence. In this paper, a new testing methodology whereby multiple stresses are applied simultaneously using a ‘design of experiment approach’ is reported. Simulated data is compared to experimental data to illustrate the potential for this technique. and a close estimation of simulated and experimentally measured lifetime is obtained. Using this data, further analysis can be conducted and show how this approach can be used for screening of the major environmental stress that leads to degradation, which could better inform manufacturers and users of the technology. One of the potential benefits of using this technique for OPV degradation studies is that additional factors could be added to

study the impact on degradation to provide a more comprehensive study.

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